BENTON HARBOR POWER PLANT LIMNOLOGICAL STUDIES.

PART II. STUDIES OF LOCAL WINDS AND ALONGSHORE CURRENTS.

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INTRODUCTION

During late spring, summer, and early fall of 1967 the directions and velocities of near-water winds and of the alongshore water currents were recorded simultaneously in front of plant site #5.

It was necessary to study the alongshore water currents because they will entrain and move the plume of warmed effluent water from the plant. The very local near-water wind conditions had to be investigated at the same time as the water currents because the area of interest is close inshore (1000 feet and less from the beach), and because the very local winds which might be expected to at least modify the alongshore currents are subject to severe topographic control by the bluff faces of the sand dunes along the shore. Topographic control of the local winds was adjudged to be so severe that wind records from the meteorological tower atop the sand dunes would probably not be applicable in the question of the control of the local alongshore water currents.

At the plant site the trend of the shoreline is north-northeast to south-southwest. About 200 feet from waterline the bluff of sand dunes arises from a grassy beach berm about three feet high; the beach rises about a foot from waterline to the base of the berm. The dunes protect the local inshore waters from winds from north-northeast, around through east and south, to south-southwest. The NNE-SSW orientation of the bluff of dune faces led us to suspect that there would be enforced channelling of winds from northerly and southerly directions into the NNE-SSW

direction. If this were true there probably would be a predominance of currents parallel to shore but under the influence of local surface winds different from those recorded by the meteorological tower on top of the dunes.

For these reasons, and also because of the spring and early summer blanketing effect of the stable spring air column (warm air over cold water) in keeping wind away from the water surface, we felt obliged to record the very local winds near to the water and separately from the meteorological tower.

METHODS

Alongshore Current Data: The regimen of alongshore currents in front of the plant site was studied by means of a tripod-supported pendulum current meter. Because the area of interest was the region between the two sand bars near shore and was subject to wave action, the entire meter installation had to be heavily built, and some sacrifice of delicacy of measurement had to be accepted, to obtain ruggedness sufficient to withstand the environment.

Built of heavy-duty 2-inch pipe braced with angle iron, the tripod-supported pendulum meter stood five feet high above an iron foot-plate under each foot. From the top of each leg a pipe member four feet long reached horizontally inward to a center iron plate beneath which a sealed iron-plate pendulum was suspended by gimbals. The pendulum contained a multiple series of modified mercury switches capable of indicating eight current directions

and four rough current speeds. The meter was secured by three earth-auger anchors screwed into the bottom, one just inside each leg. From the anchors vertical hold-down wires ran up to the outer end of the horizontal pipe members.

The meter was installed in 15 feet of water between the inner and outer sand bars in front of the cottage at the north side of the plant site. The output of the meter was transmitted by multiconductor cable to the cottage and recorded on an Esterline-Angus Events Recorder. The free-swinging pendulum of the meter could sense both wave action and current, and current direction was determined from the record by the dominance of numbers of north and west swings over south and east swings (or vice versa).

The pendulum meter was calibrated in the University of Michigan Department of Naval Architecture towing tank. Deflection of 5° (0.98 foot per second) was necessary to activate the direction-switches. Further current velocities needed to activate the subsequent velocity switches were: 2.62 ft/sec; 3.44 ft/sec; and 4.92 ft/sec. It was verified in the field that currents less than 0.98 ft/sec were all northward during the period of investigation (discussed later).

The meter withstood the wave action of winds over 30 mph, but on 11 October it was hit by a two-bushel mass of nylon fish net with incorporated driftwood moving under 35 mph winds and recorded water current of 4.92 feet per second. The impact broke a poorly welded joint where one of the legs joined its horizontal member and that side of the tripod collapsed, laying the pendulum on

bottom and stopping the recording of current. The meter was clean and still capable of operating when it was recovered on 10 November.

Wind Data: Inshore over-water winds that might be expected to be the driving or modifying force for the alongshore currents between the sand bars (at about 500 and 1000 feet from shore respectively) were recorded at 16 feet above the water by a Weather Bureau Standard Cup Anemometer and Wind Vane (sold by Science Associates, No. 440). This installation was about 50 feet out from the face of the bluff and on the grass-covered beach berm at the foot of the bluff. On a heavy wooden base and stoutly guyed, this installation performed well throughout the period of record.

Outputs from the anemometer and wind vane were led by multi-conductor cable to the Esterline-Angus recorder in the cottage, and provided a simultaneous wind record to go with the current recordings.

ACKNOWLEDGEMENTS

We are indebted to several members of the Indiana and Michigan Electric Company for help and advice at various times. Particularly we are grateful to Mr. John Banyon for unfailing help at all times. Especial thanks go to Mr. Roy Whitehead who was in residence at the cottage during part of the recording period and who tended the recorder. After he moved from the cottage his tending of the recorder involved special travel and inconvenience. Not knowing who was responsible, we extend thanks to Mr. Banyon for Indiana and Michigan's installation of rows of closely spaced light-pole

stubs at both edges of the plant site property. They materially decreased the chances of vandalism to our gear by denying the beach to local vehicles.

RESULTS

The current meter and wind instruments were installed on 11 May 1967. Recordings began at 12 noon EST on that day. Current recording continued until the current meter was disabled at 6:30 PM EST on 11 October 1967. The recordings of wind continued until 1:00 PM on 14 November.

The period of recordings covers part of the last month of spring (May), all the summer (June, July, and August), and most of the fall (September, October, and half of November), extending from cold-water conditions in late spring to cold-water conditions in late fall. It covers the summer period when conditions of warm water and the presence of summer residents are important.

The results consist of simultaneous records of wind direction and speed and current direction and speed.

Table 1 gives the relations of wind directions to the trend of the shoreline; it is these relationships that probably make the very local over-lake winds different from those recorded on the meteorological tower. This table deals only with the thirteen directions from which our wind instruments were not sheltered by the bluff of sand dunes; the seven-month mean percentages of winds from these directions are also given, as a means of indicating the effects of the shore. Calms and variable winds are not given.

Table 1.

Relation of thirteen directions of wind to the plant site shoreline.

Wind from	Orientation of wind to plant site shoreline	Seven-month mean % frequency of wind
NE	from the land	0.04
NNE	parallel to the shore	14.2
N	obliquely onto shore at about 22°	4.5
NNW	obliquely onto shore at about 45°	10.2
NW	obliquely onto shore at about 67°	1.4
WNW	onto shore at about 90°	2.6
W	obliquely onto shore at about 67°	1.0
WSW	obliquely onto shore at about 45°	3.5
SW	obliquely onto shore at about 22°	1.0
SSW	parallel to the shore	22.6
S	from the land	2.5
SSE	from the land	2.4
SE	from the land	0

The peak mean wind frequencies at NNE and SSW are considered to be shore-caused abnormalities. This suspicion is supported by the low percentages of the winds on either side of the peak frequencies. We regard the drop from 14.2% to 4.5% between NNE and N and that from 22.6% to 1.0% between SSW and SW as indicating substantial redirection of north and southwest winds as they come into contact with the dune faces. The percentages of N and SW winds also appear to be suspiciously low and indicative of wind channelling when compared to the percentages of NNW and WSW winds. Independent support for these beliefs is afforded by some comparisons made between our wind records and those from the 200-foot level of the meteorology tower.

During the first two weeks of exposure of our wind instruments they were compared under different wind directions and velocities to the 200-foot-level wind instruments on the meteorological tower.

The comparison was made under the assumption that the 200-foot level on the meteorological tower atop the dunes was relatively free of shore effects and could provide a measure of the shore effect on the surface winds driving the very local currents. These comparisons are presented in Table 2.

Table 2.

Comparisons of winds at 16 feet on the beach to those at 200 feet on the meteorological tower.

Date	Time	Beach wind at 16 feet	Tower wind at 200 feet
18 May	0600	from SSW (204°) 10.5 mph	from 204° 22 mph
	1200	from SSW (204°) 15.5 mph	from 210° 30 mph
	1800	from SSW (204°) 17.5 mph	from 200° 30 mph
	2400	from SSW (204°) 15.5 mph	from 235° 32 mph
19 May	0600	from WNW (294°) 6.2 mph	from 290° 30 mph
20 May	0000	from NNE (23°) 13.0 mph	from 0° 16 mph

Among these comparisons the diversion of an unobstructed upper level wind from 210° to a beach wind from 204° (1200 on 18 May), the diversion of an unobstructed upper level wind from 235° to a beach wind from 204° (2400 on 18 May), and the diversion of an unobstructed upper level wind from 0° to a beach wind from 23° (0000 on 20 May) are evidently redirections of lower-level wind due to its contact with the bluff of dunes. In a different sense, the redirection of a wind from 200° at upper level to a beach wind from 204° (1800 on 18 May) might be due to the wind dropping into the lee of the dune bluffs and turning to run up the beach in the lee of the dunes.

The simultaneous wind velocities in Table 2 further indicate that the very local currents are influenced by local surface winds

of considerably less speed than those at the 200-foot level on the tower.

As a check on the validity of our results we have computed the monthly ratios of mean wind velocity/mean current velocity. The norm to which these ratios are compared is Olsen's finding in Lake Erie that the surface current is "about 2%"* of the surface wind velocity. In the 15 feet of water where the current meter was installed the surface current should reach to bottom. This computation of ratios is shown in Table 3.

Table 3.

Ratios of monthly mean surface wind velocities to monthly mean surface current velocities.

Month	Wind, mph	Current, mph	Ratio: Current/Wind, in percent
May	8.0	0.13	1.6%
June	5.6	0.07	1.3%
July	6.9	0.10	1.4%
August	7.1	0.13	1.8%
September	6.4	0.12	1.9%
October	9.3	0.15	1.6%
			Grand Mean 1.6%

Within the limits of the norm, our results appear to be valid. The fact that none of the ratios attains to 2% is undoubtedly an effect of bottom friction, for the pendulum of the current meter cleared the bottom by only about eight inches.

*See: Hutchinson, G. E. A Treatise on Limnology. Volume I, John Wiley & Sons, New York, 1957, page 291.

The Local Surface Winds: From our beach installation the distributions of percent of hours that the wind blew from the 13 usable directions (also calms and variable winds) was as shown in Table 4.

Calms and High Winds: The distribution of mph wind speeds in percent of the hours, and monthly weighted-mean wind speeds are given in Table 5.

Table 5.

Percent distribution of wind speeds, mph, and monthly mean speeds.

Month	Calm (0-3mph)	4-12mph	13-24mph	25-38mph	>38mph	Monthly Mean
May	27.0%	55.9%	17.1%	0%	0%	8.0 mph
June	41.5	55.6	2.9	0	0	5.6
July	33.4	56.1	10.5	0	0	6.9
August	37.9	48.0	13.6	0.5	0	7.1
September	47.2	39.4	13.2	0.2	0	6.4
October	24.2	50.3	23.8	1.7	0	9.3
November	23.2	45.0	29.7	2.1	0	10.1

This tabulation follows Resolution 9 of the International Meteorological Committee, Paris, 1946. The allocation of "Calm" to all winds of 3 mph or less is also a recognition that our anemometer and wind vane required about 4 mph of wind to operate accurately.

Table 5 shows that the highest percents of calm hours occurred during June and September. Calm conditions may be expected to provide minimal dispersion of the heated plant effluent; wave action would be absent, and the effluent would drift with the residual current remaining from the previous wind. While the

Table 4.

Percentage of hours that the wind blew from:

Month	NE	NNE	N	NNW	NW	WNW	W	WSW	SW	SSW	S	SSE	SE	Calm	Variable
May	0.3	29.7	4.0	14.2	0.3	2.1	0.3	2.1	0.5	12.8	1.6	2.7	0	27.0	2.4
June	0	9.0	5.2	6.1	0.6	0.1	0.1	0.4	0.4	29.7	2.4	3.6	0	41.5	0.9
July	0	8.3	11.3	8.3	3.0	2.5	0.8	2.4	1.3	23.0	2.5	2.9	0	33.4	0.3
Aug.	0	21.5	2.3	9.9	0.3	1.5	0	2.7	0.1	17.9	1.8	3.6	0	37.9	0.5
Sept.	0	17.8	5.1	6.7	0.5	2.2	0.8	1.8	0.8	14.8	0.5	1.6	0	47.2	0.2
Oct.	0	6.8	2.8	11.7	2.6	4.9	1.4	9.1	1.3	29.6	3.6	2.0	0	24.2	0
Nov.	0	6.2	1.0	14.2	2.4	4.8	3.8	5.9	2.8	30.2	5.2	0.3	0	23.2	0
Means	0.04	14.2	4.5	10.2	1.4	2.6	1.0	3.5	1.0	22.6	2.5	2.4	0	33.5	0.6

percents of calm hours are high in June and September, their mere numbers do not indicate the numbers of consecutive calm hours during which residual currents might die away. This condition is examined in Table 6.

Table 6.

Daily maximum consecutive hours of calm. Night calms extending past midnight are added to the following day.

Date	May	June	July	Aug.	Sept.	Oct.	Nov.
1		2	2	15	14	20	18
2		5	1	9	16	0	1
3		0	3	13	17	0	3
4		24	2	0	16	0	0
5		18	7	16	15	3	0
6		11	13	14	15	2	0
7		8	5	0	19	13	14
8		1	9	16	22	0	17
9		0	1	0	0	0	0
10		1	24	0	2	0	20
11	0	5	6	6	16	2	0
12	0	2	3	16	17	7	0
13	12	4	0	16	14	--	0
14	14	2	0	9	--	0	0
15	6	1	12	8	--	15	
16	12	2	13	9	0	0	
17	4	2	2	0	19	8	
18	0	3	2	2	17	0	
19	0	14	3	4	11	0	
20	0	4	--	4	10	7	
21	10	21	--	0	0	0	
22	0	9	0	1	5	15	
23	--	11	1	16	10	2	
24	--	5	5	15	2	0	
25	--	4	5	14	8	0	
26	--	3	8	12	0	0	
27	0	14	6	0	0	7	
28	5	6	4	7	1	0	
29	0	2	9	4	9	27	
30	12	0	0	0	0	8	
31	1		11	3		11	

It is evident from the table that the great majority of calms during the summer months are of a few hours duration during which

it would be unlikely that the alongshore current would die away. During the first three weeks of September long periods of calm were dominant; under these conditions removal of warmed effluent by currents would be poor.

Highest velocities of surface wind occurred sporadically in August (Table 5) and, to judge from the reduced hours of calm beginning 21 September (Table 6), entered the picture again in the last week of September. High winds increased in frequency during October and November. The greater wave action and current movement accompanying such winds would provide improved dispersal of the effluent.

The Very-Local Currents: The percentage distribution of alongshore water current directions and of currents too slow to activate the meter's direction-switches are given in Table 7.

Table 7.

Percent of hours the current flowed toward:

Month	NE	N	NW	W	SW	S	SE	E	Too low to record direction (<0.98 ft/sec)
May	0%	9.1%	62.3%	3.0%	0.3%	0%	0%	0%	25.3%
June	0	2.0	29.9	4.8	0	0	0	0	63.3
July	0	2.9	51.3	2.9	0	0	0	0	42.9
Aug.	0	4.1	50.2	1.8	2.3	1.8	0	0	39.8
Sept.	2.2	6.5	29.2	2.2	2.2	3.0	0.8	0	53.9
Oct.	0.3	12.0	45.1	4.4	3.6	5.7	0	0	28.9

The two outstanding features of this table are the predominance of recorded currents toward the northwest and of currents too low to activate the direction-switches of the meter.

Except for one hour in May, the current between the sand bars flowed toward north, northwest or west throughout May, June, and July. During these months the current flowed to these directions regardless of wind direction or wind velocity.

On August 9th the first southward current since the one hour in May was recorded. After this, current to southward directions became progressively more frequent.

Independent determinations of current direction at the meter site were made by float runs at several times during the summer. On all these occasions the current was moving northward; on some of these occasions the meter was recording northward current, on others the current was too low to record direction. On 7 August our divers inspected the meter; it was clean and operating properly; the meter was recording northward current and the divers measured northward current beside it.

The August southward currents were recorded after brisk winds from northerly directions had blown for some hours. As the fall progressed, less velocity and duration of these winds were needed to produce southward current. In a few cases the recorder was not operating when southward current began, but in every case where the beginning of southward current was recorded it began abruptly after current to the northward had been being recorded.

The evidence from our float tests and other field measurements and from the recorded beginnings of south current is that the current during the too-low-to-record condition was always to the northward directions.

This being the case, the too-low-to-record-direction column of Table 7 should be added to the northward (NE, N, and NW) currents. If this is done, and SW, S, and SE currents are combined, Table 7 recombines as in Table 8.

Table 8.

Percent of hours current flowed northward, westward, and southward.

Month	Current Northward	Current Westward	Current Southward
May	96.7%	3.0%	0.3%
June	95.2	4.8	0
July	97.1	2.9	0
August	94.1	1.8	4.1
September	91.8	2.2	6.0
October	86.3	4.4	9.3

From this we conclude that, if 1967 was reasonably normal, and if the warmed effluent from the plant is discharged between the sand bars, the effluent will in the vast majority of the cases during the critical warm months travel northward or westward away from the near-by water intakes of Bridgman and Orchard Beach. Our evidence still is that the plume of warmed water would not reach the St. Joseph water intake nine miles to the north.

The distribution of weighted-mean water current velocities during the months of recording are given in Table 9.

This table shows maximum frequencies of lowest current speeds in June and in September, lowest monthly mean current velocities in June and July with third-lowest in September, and a steady increase in current velocities in the 3.44 to 4.92 ft/sec range

from June through October. In most respects it is very similar to the behavior of the causative winds as shown in Table 5. Perhaps its most important aspect is that the percentage of very low currents in September is not so low (by nearly 10%) as in June, implying that the conclusions drawn from Table 6 may not be so unfavorable as percentages of calm winds alone would indicate.

Table 9.

Percent distribution of water current speed in ft/sec., by hours.

Month	0-0.98	0.98-2.62	2.62-3.44	3.44-4.92	>4.92	Monthly Mean
May	25.3%	47.0%	15.6%	12.1%	0%	.195 fps
June	63.3	32.7	3.0	1.0	0	.104
July	42.9	38.3	11.6	7.2	0	.155
Aug.	39.8	25.0	17.7	17.5	0	.192
Sept.	53.9	12.6	5.6	27.4	0.5	.184
Oct.	28.9	27.9	14.6	28.6	0	.229

<u>The Climatological Representativeness of 1967</u>: As a means of climatological comparison, the winds and air temperatures at Muskegon during the months of May through October were compared to the 30-year averages for these months. The departures of these parameters from the 1931-1960 averages are summarized in Table 10.

Table 10.

1967 departures from the 30-year normals.

Month	Air Temperature	Wind Velocity
May	-3.3°F	+0.5 mph
June	+2.7	-0.1
July	-1.5	+0.6
August	-3.8	+0.1
September	-1.9	-1.5
October	-1.6	+0.5

Except for the month of June, the summer was one of the coolest on record in the Midwest. Windwise, the months of June and August were about normal; May, July and October had somewhat more wind than normal; and the winds of September were substantially below normal.

The cooler air of May established over the lake a weaker than usual thermal inversion (warm air over cold water) through which the above-average May winds could more easily break to impart momentum to the water. Therefore, the observed current velocities of May must be considered higher than normal.

The above-normal winds of July and October, to which considerations of stability do not apply, also would produce greater current speeds than normal.

The decrease in mean current speed observed in September resulted from subnormal winds and an anomalous frequency of calms. September currents must be regarded as slower than usual.

In the typical year, wind velocities become progressively greater from June through November and should be reflected in the mean current speeds.

Considering all the data, it appears that in the normal year there should be no material danger that the alongshore current would die out for more than very short periods of time.

DISCUSSION

The current-direction results presented above are in accord with our best recent information about the underlying causes of alongshore currents. They are also compatible with our older

ideas about basic circulation patterns in the lake.

Spring warming of the lake begins in the shallow water along shore, while the main body of the lake is still at temperature of maximum density (4°C) or lower (continued wind-mixing in winter drives down and mixes in surface water cooled below 4°C by contact with colder winter air). In spring the warmed shallow water along shore is expanded and less dense; it creates, between the cold main body of the lake and the warm shore, an alongshore sloped water surface that tilts upward toward the land. On this sloped water surface there will be, as a resultant of the earth's rotation (Coriolis force) and gravity, a tendency for establishment of a geostrophic circulation in which water current runs in such direction that the elevated part of the water surface is on the current's right (observer's right when he looks downcurrent). At the plant site the warmed inshore water makes a tilted water surface on which a current runs toward the north. In all seasons the prevailing westerly wind pushes surface water of the main body of the lake toward the east shore; in spring this push (wind set-up) narrows the alongshore belt of tilted water surface, increases the tilt of the tilted water surface, and strengthens the tendency toward northward-flowing current.

By late spring or early summer the inshore warming has extended to greater depths and to a greater distance from shore, reducing the area of very cold surface water in the main body of the lake. In the alongshore areas where the warmed water has reached completely to bottom, the basic local summer pattern of current eddies

begins to establish itself. Thus by June the elongate narrow inshore counterclockwise eddy lying between Michigan City and Benton Harbor (identified by "x" in Figure 4 of Part I of this report) could have been established, though a reduced area of surface water of 4°C or less was still present in the main body of the lake. The surface slope due to warmest water against shore, aided by wind setup narrowing and steepening the slope, favors the northward geostrophic current on the slope and reinforces the inshore northward-moving half of the Michigan City-Benton Harbor eddy. The offshore southward-moving half of the eddy would be opposed by the geostrophic tendency and probably break down into small mixing vortices contributing to the warming of the deep-basin water.

As the summer progresses continued warming of the lake from shore toward the center eventually establishes a thermocline across the lake but, through July, surface temperatures of water in midlake are less than those along shore. The temperature-created tendency for a sloped surface tilting upward toward land is less as midlake-to-shore temperatures become more nearly alike, but wind setup still pushes surface water against shore to strengthen and maintain the slope upward toward land. Geostrophic northward current along shore should then still be the rule, but the offshore south-moving half of the Michigan City-Benton Harbor eddy is probably established and flowing.

By August the thermocline has been established and pushed to full depth across the whole of the lake, though slightly cooler surface temperatures are present in midlake than at the shores. The temperature induced slope upward toward land is now at its

weakest and is maintained largely by wind setup pushing warm surface water against shore. Northerly winds can now begin to overpower the geostrophic tendency to north current and can drive the Michigan City-Benton Harbor eddy south of the plant site or wipe it out temporarily. Southward currents at the plant site appear when the eddy is out of the region.

In September autumnal cooling has begun and the shallow inshore waters become cooler than the warm midbody of the lake. Cooler, contracted, more dense water alongshore now tends to produce a sloped water surface tilted upward toward midlake; this tendency to tilt is, however, opposed by wind setup pushing warm midlake surface water against shore. Northerly winds, temporarily replacing the prevailing westerlies, can now eliminate the wind setup and more easily and frequently than before produce southward flowing current at the plant site, by pushing the eddy south or wiping it out. Southward currents should now occur more frequently at the plant site, as is observed.

Continued autumnal cooling, progressing from shore lakeward, produces increased tendency for a water surface tilted upward toward midlake, for the shallow water cools faster than the deep. Prevailing westerly winds still overpower this tendency by pushing warm surface water from midlake against the shore, but now wind setup is working against a strengthening geostrophic tendency for clockwise circulation around the lake (southward currents at the plant site). Cessation of the prevailing wind is now more quickly and more frequently followed by southward current at the plant site,

as is observed in October. In all probability the Michigan City-Benton Harbor eddy is now being wiped out more frequently, but evidence is lacking.

Currents Inshore of the Inner Bar: We have a limited number of observations of current direction in water immediately against the beach inshore of the inner sand bar. On every occasion current here was moving in the downwind direction.

Apparently the water between the sand bars partakes in the most inshore part of the main-lake circulation, and the dominant north-south movements there may well be important factors in the maintenance of the two sand bars.

Water inshore of the inner sand bar appears to be water which has spilled over the inner bar during surf action and which is cut off from the main-lake circulation by the inner bar. Cut off from the main-lake circulation, this water is subject only to the alongshore component of the wind blowing at the moment and its movement is downwind. If the plant effluent is discharged between the sand bars, it may be expected that under winds from north quarters some of the effluent will work across the inner bar to join the southward flow along the beach. Under winds from south quarters the spillage over the inner bar would move northward along the beach.

The undesirable southward flow inside the inner bar under northerly winds plus the dominant northward flow between the bars under all winds are both reasons that the plant effluent should be discharged between the sand bars, as recommended by letter to Joel Gingold on 7 September 1967.